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ENERGY LEVELS IN Co^{60}

George Melvin Foglesong
and
David Guy Foxwell

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1954

THESIS
F53

Letter on front cover:

ENERGY LEVELS IN Co^{60}

George Melvin Foglesong
and
David Guy Foxwell

ENERGY LEVELS IN Co^{60}

by

George Melvin Foglesong

B.S., U.S. Naval Academy
(1945)

and

David Guy Foxwell

B.S., U.S. Naval Academy
(1947)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June, 1954

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TABLE OF CONTENTS

Page

ACKNOWLEDGMENTS

ABSTRACT

I. INTRODUCTION 1

II. DESCRIPTION OF APPARATUS AND TARGET PREPARATION 6

A. Apparatus 6

B. Target Preparation 12

III. EXPERIMENTAL PROCEDURE 15

IV. RESULTS AND CONCLUSIONS 27

A. Probable Error 27

B. Results 34

C. Comparison with Previous Results 36

D. Conclusion 36

APPENDIX A 42

BIBLIOGRAPHY 44

ENERGY LEVELS IN Co^{60}

by

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Submitted to the Department of Physics on May 24, 1954 in

partial fulfillment of the requirements for the degree of

Master of Science

ABSTRACT

Proton groups from the reaction $Co^{59}(d,p)Co^{60}$ were examined in order to determine the ground state Q-value and the excitation energies of the lower lying excited states of Co^{60}. Platinum-backed naturally mono-isotopic cobalt targets were bombarded with magnetically analyzed deuteron beams from the MIT-ONR Van de Graaff generator, and the protons emerging at 90° to the incident beam were analyzed by a 180° focusing magnetic spectrograph and photographically detected.

The targets were made by vacuum evaporating cobalt pellets onto platinum sheets cleaned with hydrochloric acid. The high boiling point of cobalt required the use of a technique of pinching the pellets between sharpened carbon electrodes. Spectro-chemical analysis of the cobalt showed impurities of nickel, magnesium, and copper, with lesser amounts of other metals. Known levels in nickel and magnesium could be identified with smaller proton groups, but, owing to the rather high background and density of levels, not conclusively. Levels assigned to cobalt were confirmed by noting the variation of the proton group energies with deuteron energy. Bombarding energies of 5.0 and 5.8 Mev were used.

The ground state Q-value was measured as 5.280 ± 0.008 Mev. The metastable state, observed in beta- and gamma-ray decay measurements at 58.5 ± .5 kev and seen here for the first time in any nuclear reaction, was measured as 60 ± 3 kev. Other low lying excited states agree with those previously determined by (n, γ)

reactions, and further identify the most energetic gamma-ray seen in these reactions as being that to the ground state of Co^{60}. The higher excited states, while in poor agreement with the corresponding (n, γ) results, showed a complex level structure, as was expected for this odd-odd nucleus, and as was indicated in the (n, γ) work.

Thesis Supervisor: W. W. Buechner

Title: Associate Professor of Physics

I. INTRODUCTION

M.I.T. Van de Graaff generators have been used extensively over the past few years to obtain precise information on the nuclear energy levels of various light and intermediate nuclei. These accelerators, when coupled with magnetic momentum analyzers and magnetic spectrographs, provide data of a high degree of accuracy and resolution. The concentration of effort has been on light nuclei, where it is felt that the relatively few nucleons should lend themselves to a detailed treatment of nuclear forces, particularly if some of them can be grouped into closed shells. The emergence of isobaric polyad structure has supported the idea of charge independence of nuclear forces, but, to date, only limited success has been achieved in the formulation of a theory of nuclear forces.

The completion of a new accelerator, designated the MIT-ONR Van de Graaff generator, about two years ago extended the available bombarding energy from 2.0 Mev to 8.5 Mev and opened up the possibility of accurate measurements of the energy levels of heavy nuclei. Two specific problems dealing with naturally mono-isotopic nuclei were suggested to the authors by Dr. W. W. Buechner:

(1) The apparent 0.4 Mev discrepancy in the following cycle[1] of ground state Q-values and decay energies which would most logically be attributed[2] to an incorrect assignment of the ground state of Bi^{210}: Pb^{206}, Pb^{207}, Pb^{208}, Pb^{209}, Bi^{209}, Bi^{210}, Po^{206}; and,

(2) The indeterminancy of the location of the ground state of Co^{60} in relation to the excited states of Co^{60} as given by Bartholomew and Kinsey,[3] and the questionable spin assignments of the ground and first excited states of this nucleus.[4]

While the first problem was not solved because of a temporary reduction in the maximum attainable voltage with the MIT-ONR generator, tentative results were promising. In pursuing the $Bi^{209}(d,p)Bi^{210}$ reaction, preliminary results with a bombarding energy of 8 Mev indicated that previously reported proton groups corresponding to the excited states of Bi^{210} could be resolved, and the question of the ground state might well be answered by this approach.

Investigation of the second problem did not require such a high bombarding energy. The most reliable source of information on energy levels in Co^{60} lies in the (n, γ) work of Bartholomew and Kinsey.[3] While their results indicate relative positions of the excited states, they cannot determine whether their lowest state is attributable to the actual

ground state or to the well-known metastable state at 58.9 ± 5 kev[5]. Previous Co^{60}(d,p) analyses, by Bateson and Pollard[6], Hoesterey[7], and Harvey[1], had resulted in ground state assignemnts in which the ground and first excited states were not resolved. This earlier work had been done with cyclotron deuterons and aluminum foils, and was, by its nature, of moderate accuracy and poor resolution.

The question of the spin assignments of the ground and first excited states was brought up recently by the discovery of a new beta-ray from the ground state of Co^{60} to the first excited state of Ni^{60} as is shown in Figure 1. Keister and Schmidt[4] were led by the shape of the Kurie plot of this beta to the spin and parity assignments of 4+ and 1+ to the ground and metastable states of Co^{60}, respectively, in contrast to the generally accepted values of 5+ and 2+. These new assignments, however, cannot be reconciled with the lack of beta decay from the first excited state of Co^{60} to the ground state of Ni^{60}. This question might have been resolved by using the rotatable magnetic spectrograph currently under development for use in conjunction with the MIT-ONR generator. The angular distribution of the protons and, from Butler's theory[9], the orbital angular momentum of the captured neutrons might have led to unambiguous spin assignments, as is outlined in Appendix A. Unfortunately, the new spectro-

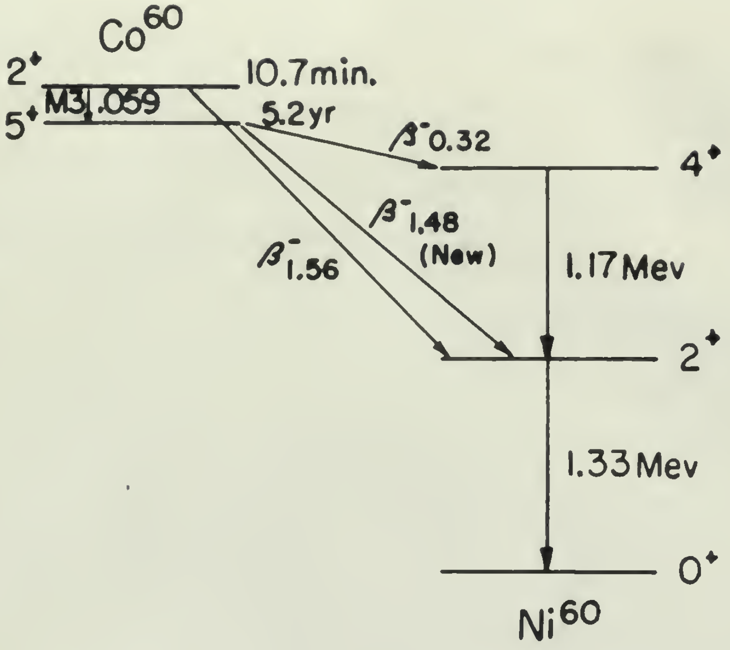


Figure 1

ENERGY LEVEL DIAGRAM SHOWING DECAY SCHEME OF Co^{60}

graph was not completed in time to include such an analysis in this work.

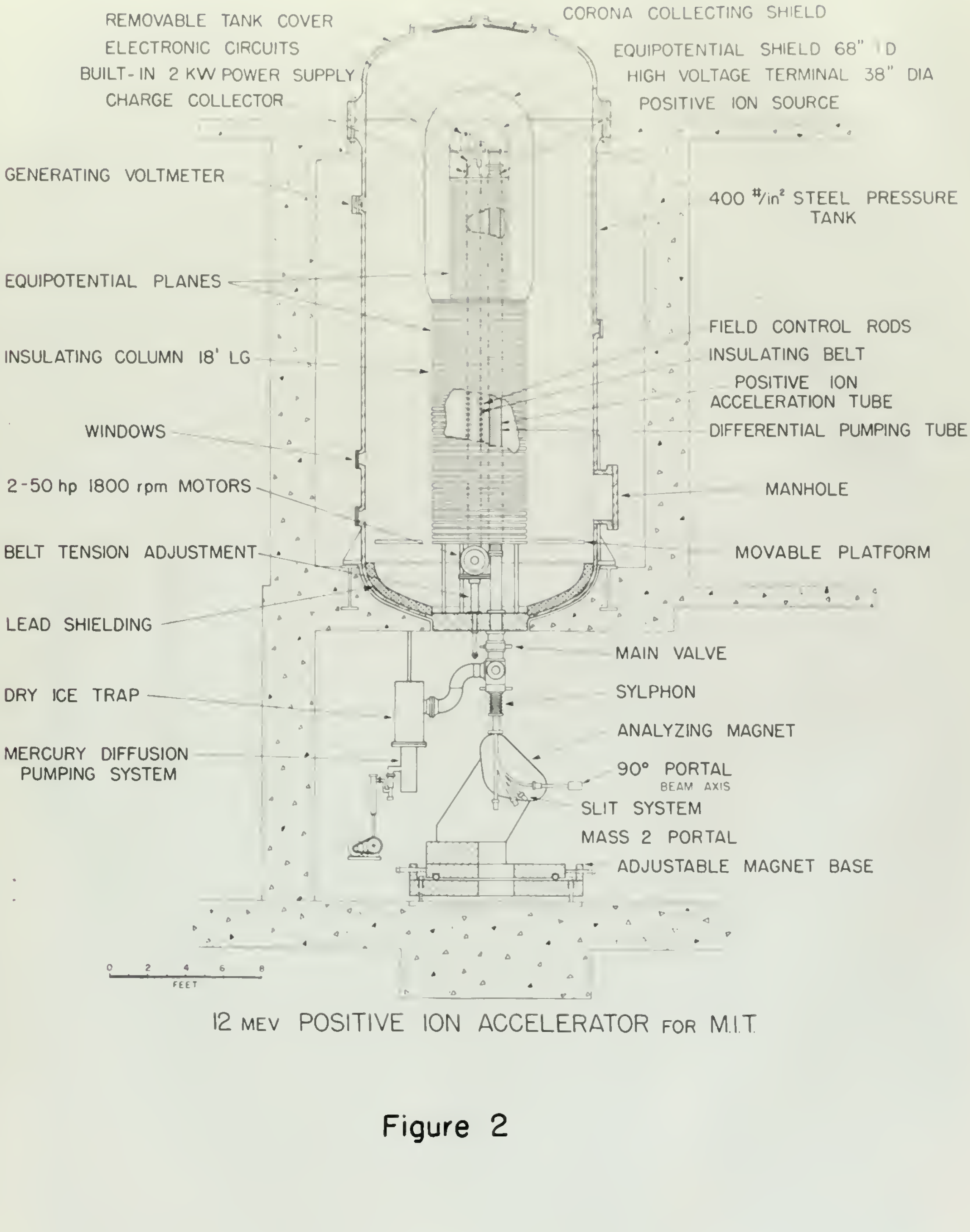
The problem, then, was to determine the Q-value of the $Co^{59}(d,p)Co^{60}$ reaction to the ground state of Co^{60}, with a secondary purpose of checking the levels of excitation against those previously seen, particularly those levels about which Bartholomew and Kinsey were in doubt.

II. DESCRIPTION OF APPARATUS AND TARGET PREPARATION

A. APPARATUS

The MIT-ONR Van de Graaff generator, used as the source of deuterons for the $Co^{59}(d,p)Co^{60}$ reaction, is shown schematically in Figure 2. Its salient features include a pressurized tank designed for 400 psi, two 18 foot accelerating tubes (of one-inch-thick glass), a string controlled RF ion source capable of ionizing hydrogen, deuterium, or helium, a focus voltage supply capable of providing 40-80 kv, and a controlled corona discharge grid. The deuteron beam is deflected through 90° by an analyzing magnet, after which it strikes the target in the spectrograph (Figure 3).

The energy of the deuteron beam is defined and controlled by means of a one mm slit 90 cm above the analyzing magnet and a 1/2 mm slit 185 cm beyond the analyzing magnet. A given magnetic field in the analyzer determines the momentum of a charged particle which will pass through the slit system. The difference between the currents to the upper and lower exit slits is amplified and this signal is used to control the voltage in the corona discharge grid, thus providing terminal voltage control. This control is satisfactory for terminal voltages down to about 4.5 Mev. The analyzing magnet can be rotated about a vertical axis so as



12 MEV POSITIVE ION ACCELERATOR FOR M.I.T.

Figure 2

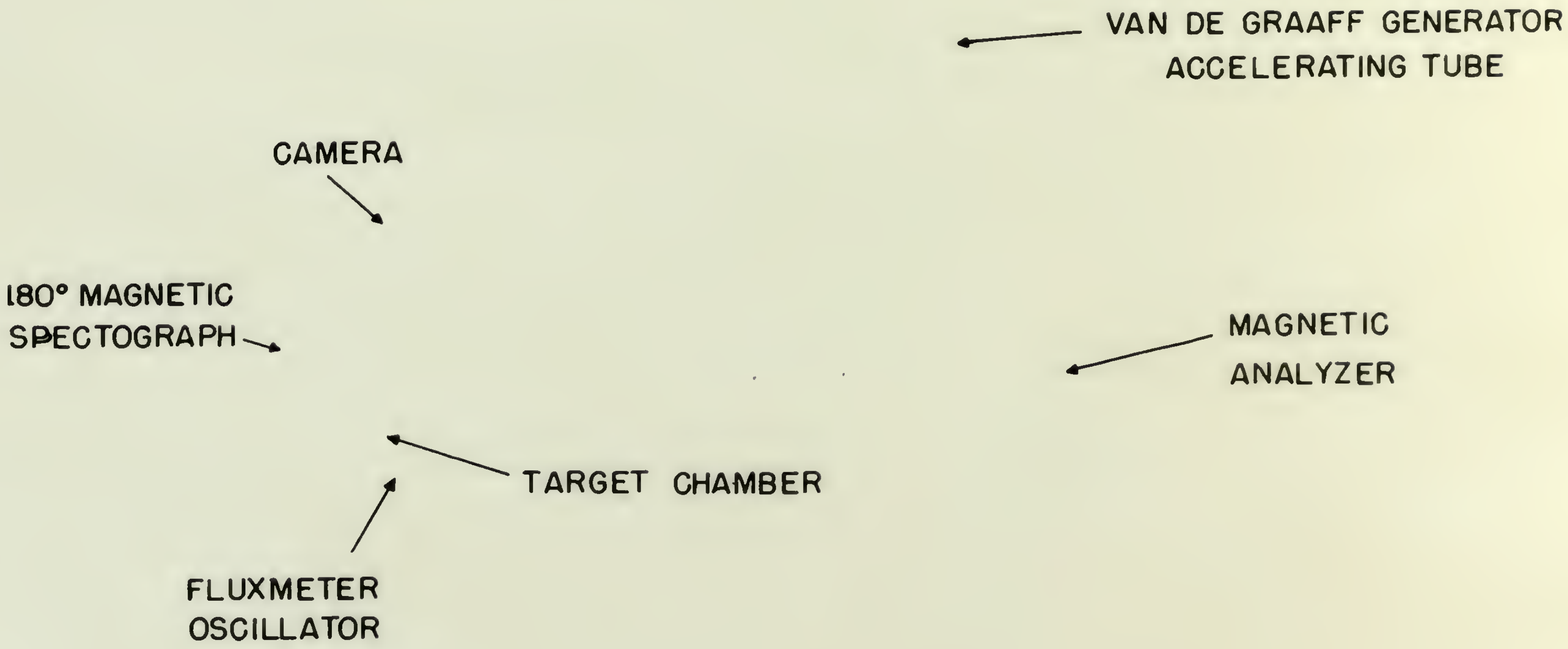
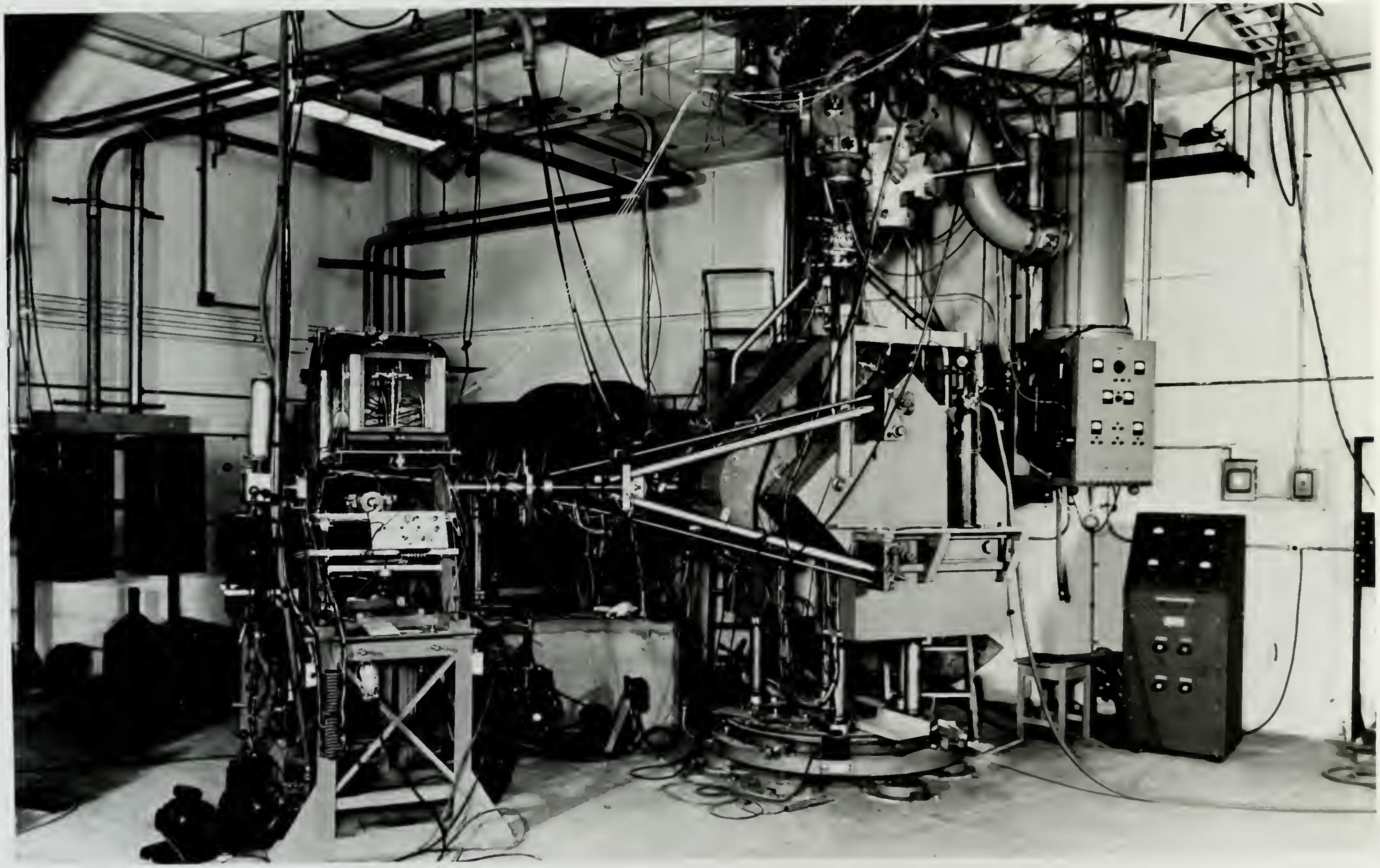

VAN DE GRAAFF GENERATOR
ACCELERATING TUBE
CAMERA
180° MAGNETIC
SPECTOGRAPH
MAGNETIC
ANALYZER
TARGET CHAMBER
FLUXMETER
OSCILLATOR

Figure 3



to deflect particles either to a fixed, 180° focusing magnetic spectrograph, which observes reaction products only at 90° from the incident beam, or to the new rotatable spectrograph. Only the fixed magnet was used in this work.

The fixed magnetic spectrograph is fitted with entrance slits to define the beam position and energy, and a Faraday bucket arrangement for measuring beam current. The bottom of the annular magnet is slotted to accept the incident particles. A detailed account of this spectrograph is given by Strait.[10]

The charged particles from the nuclear reaction which emerge in the acceptance angle of the spectrograph are deflected with a radius proportional to their momentum and recorded on a 1" X 2" Eastman NTA nuclear track plate placed in a slot along the top of the magnet. These track plates are positioned with their long dimension vertical and with the normal to the emulsion at about 70° from the incident particles in a carriage which can hold, and position in turn, five such plates. A light, prism, and slit arrangement is available to "index" the plates at a fixed vertical position.

The magnetic fields in the analyzing and spectrographic magnets are determined by a nuclear resonance technique,

utilizing the known gyromagnetic ratio of the Li^7 nucleus. Each magnet is equipped with a high frequency oscillator whose loading coil surrounds a capsule of a lithium salt solution placed in the field. In operation the oscillator is "zero-beated" with a secondary frequency standard and the current to the magnet is increased until the oscillator output is decreased, indicating resonance. Resonance is observed by sweeping the field in the vicinity of the capsule with a weak 60 cycle field and displaying the detected output of the oscillator on the vertical sweep of an oscilloscope which is swept in the horizontal direction with this same 60 cycle signal. When resonance is achieved the oscillator will be loaded twice a cycle with an angular displacement of 180° , and the two depressions on the scope face will be opposite each other. As the field current drifts from the correct value, the angular separation of the two depressions (loadings) will decrease, indicating that magnetic resonance is occurring only near the upper or lower variation of the sweep field. A phase control permits setting a variable phase between the 60 cycle sweep signal and the detected oscillator output, so that the two depressions may be superimposed. The magnet current is adjusted so that signals remain displaced by 180° as the sweep current is made vanishingly small. The error intro-

duced by virtue of the fact that the two depressions are not exactly 180° apart can best be estimated by varying the signals as a function of zero-beat frequency. When this is done it seems that the sensitivity of the visual signal is about .5 kc at a frequency of 19.0 mc. The zero-beat frequency itself, on a reasonably careful run, is kept below 1 kc, so that the reproducibility of the magnetic field at the capsule is in error by about one part in 20,000 (1:20,000).

The known gyro-magnetic ratio of the lithium nucleus is used to determine the magnetic field, assumed to be the effective field experienced by the charged particles. This assumption, which may be in error by perhaps .1%, leads to a very small error in measured momenta, as is seen below. The diameter of the trajectory in the spectrograph from the target spot to the index is determined by use of a polonium-coated wire at the target position. The BR of polonium alphas is 331.588 ± .02% kilogauss-cm.[11] The wire to beam spacing is measured with a microscope to ±.05 mm, and is very small compared to the diameter. The fractional error in magnetic field, dB/B, yields a fractional error, $dR_a/R_a \simeq -dB/B$ in the measured radius of the path from polonium wire to the alpha tracks on the emulsion, where R_a = radius of trajectory of alpha particles.

In measuring momenta of charged particles from nuclear

reactions, the error introduced is then $BdR - RdB = -dBR_a - RdB = dB(-R_a - R)$, where R = radius of the trajectory of these particles. We have assumed that dB/B is constant and that $dR_a = dR$.

The average radius is 35 cm and the useable portion of the emulsion is 3.5 cm, so that the maximum difference $(R - R_a)$ is .9 cm, or 2.5%. The total error due to non-uniformity of the magnetic field is then less than 1 part in 40,000. It is seen that a 0.1% error in the value of the magnetic moment of the lithium nucleus would lead to an equally negligible error. The validity of the assumption of a constant dB/B may be questioned at high fields (because of the air gaps and saturation) and this may account for a suspected decrease in accuracy for fields over 13 kilogauss.

B. TARGET PREPARATION

Thin targets, when bombarded by charged particles, yield the advantage of a sharp group of reaction products, inasmuch as the degradation of the energy of the incident particles is slight. A common method of preparing thin metallic targets is by the evaporation in a high vacuum of the desired metal onto a thin ($\sim 1000\mu$) Formvar film. This method becomes difficult with high boiling point metals, and in spite of the adoption of the method used by Schwager and

Cox[12] to evaporate vanadium, only a limited success was realised with cobalt. The extreme boiling temperature (approximately 3000°C) caused all those Formvar backings which survived to be extremely brittle, and the explosive nature of the boiling riddled the targets with small holes. Coating the reverse side of the Formvar with gold did not help to any extent. The maximum thickness of cobalt successfully evaporated in this fashion was something less than one-half that required to make a microscope slide opaque to sunlight. These targets, when exposed to deuteron beams of reasonably long exposures, yielded proton groups too weak to reduce the statistical fluctuations to an acceptable value. Recourse was then had to acceptable platinum backed targets. A sheet of platinum about 5 mils thick was carefully cleaned with hydrochloric acid and exposed in a vacuum to vaporized cobalt. Two one-fourth inch carbon electrodes were mounted vertically, with the lower rod hollowed out to hold a small piece of cobalt and necked down immediately below to perhaps one-tenth its original area, and the upper rod sharpened to a dull point and pressed down on the cobalt. The platinum was placed much closer than the Formvar had been, and a coating equal to that which was just greater than opaque to sunlight on a microscopic slide was achieved after several evaporations. It may be wondered whether the

sputtering which previously pierced the Formvar did not spatter the platinum in a random fashion, and such may indeed have been the case, although no evidence of this was seen in the results.

These targets were fixed to small rods and, for bombardment, mounted on a target wheel located just below the slot in the spectrographic magnet. Seven such targets could be mounted on the wheel and any one could then be rotated into the beam without breaking the vacuum. The targets were placed so that their normals were at approximately 50° to the incident beam and 40° to the annular chamber. When solid targets were used, the beam current integrator, developed by Enge,[13] was connected to the target wheel rather than to the Faraday bucket.

III. EXPERIMENTAL PROCEDURE

In the process of identifying and measuring the proton groups from cobalt, the first step was to bombard a Formvar-backed target with protons and analyze the elastically scattered proton groups for the mass of the scattering nuclei in order to determine the contaminants. For scattering at 90° from a target initially at rest, we get, non-relativistically,

$$m = \frac{E_{in}m_p + E_o m_p}{E_{in} - E_o}, \qquad \text{where } m_p = \text{proton mass.}$$

E_o, the energy out, is measured by recording the density of proton tracks per one-half mm (measured radially) along the nuclear track plate, to within .04 mm as the plate is traversed in a vernier-calibrated microscope stage. Protons, deuterons, and alpha tracks can be distinguished by their length and density of ionization. The index is recorded to the nearest .02 mm. The points then obtained are graphed, a curve is faired through them, and the position of the third height is noted. This position has been found to give the most reproducible results, regardless of peak intensity or target thickness, and the index to third height differences, when measured with different microscopes, have been found to have a probable error of about .15 mm. This distance is then subtracted from the index to beam distance, as measured by the

polonium alphas, and the result halved to get the radius. The magnetic field is taken as a fixed constant multiplied by the frequency of the oscillator and, as seen before, this should introduce no significant error. The product of radius and magnetic field, BR, is then converted to proton energy by means of an extensive table calculated from

$$E_p = 4.7898 \times 10^{-11}(BR)^2 - 1.223 \times 10^{-24}(BR)^4$$

E_{in}, the energy in, is determined from elastically scattered particles from a known mass such as Co^{59}, or O^{16}. Figure 4 presents a graphic mass analysis, with the most probable contaminants indicated.

The first known excited state[8] of Co^{59} is 1.10 Mev, from which level the inelastic protons would have insufficient energy to appear in Figure 4. Those mass numbers between 48 and 80 are not separated from the Co^{59} peak. It is seen that Na^{23}, Mg^{24}, S^{32}, Cl^{35} and K^{39} are present. A spectrochemical analysis of the cobalt pellets indicated the following contaminants:

Ni: 10% to .1%

Mg and Cu: 1% to .01%

Ca, Fe, and Mn: .1% to .001%

Ag, Al, B, Ba, Cr, Si, and Zn: less than .01%

The sodium, potassium, and sulphur, seen in the mass analysis of a Formvar target, probably originate in the Formvar

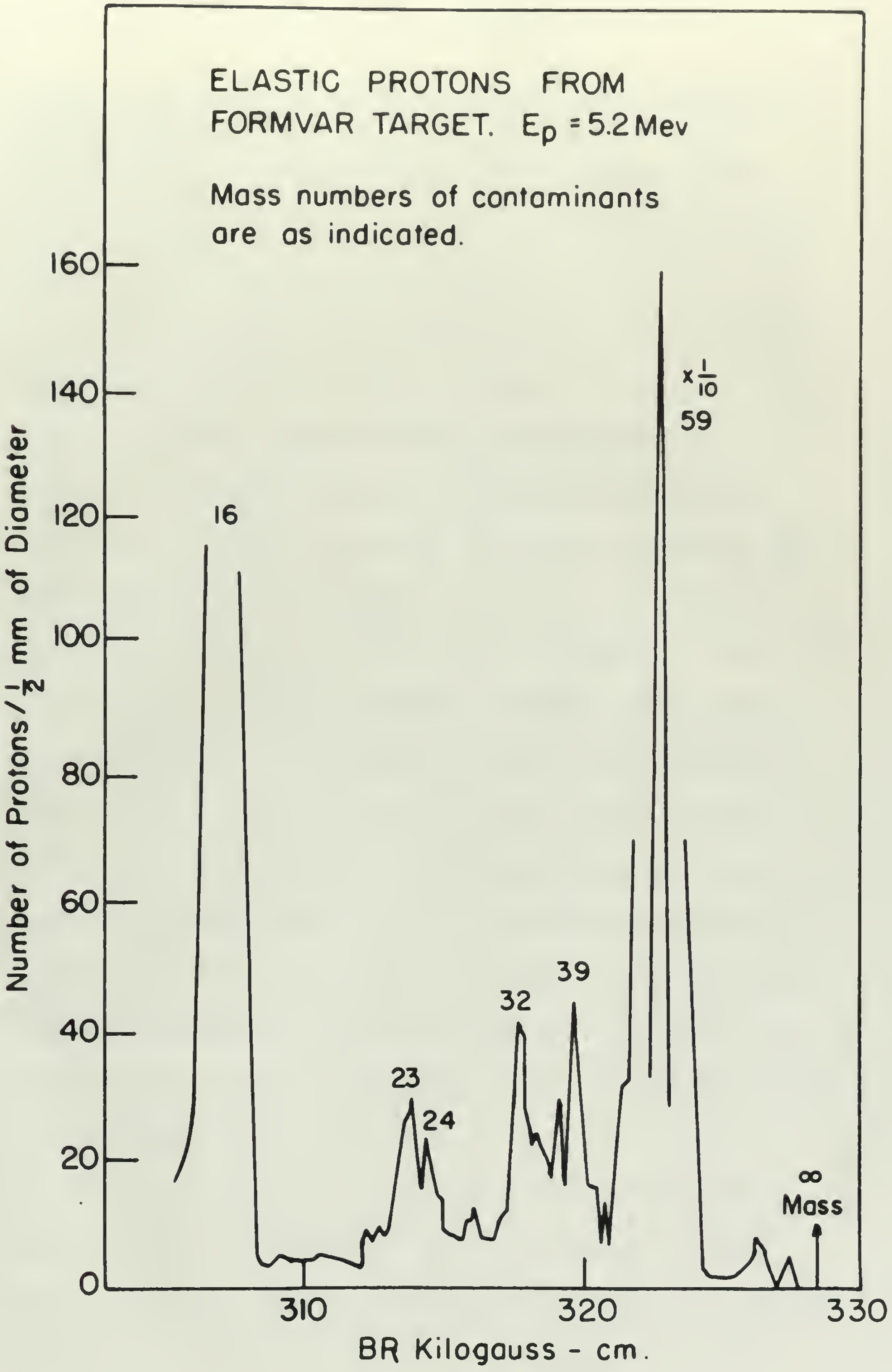

ELASTIC PROTONS FROM FORMVAR TARGET. E_p = 5.2 Mev
Mass numbers of contaminants are as indicated.
Number of Protons/$\frac{1}{2}$ mm of Diameter
0
20
40
60
80
100
120
140
160
16
23
24
32
39
×$\frac{1}{10}$
59
∞
Mass
310
320
330
BR Kilogauss - cm.

Figure 4

backing, and hence should not contribute proton groups in the bombardment of the platinum-backed targets. Groups from the platinum itself, if present, should be very broad, because of the thickness of the backing.

Formvar targets coated with cobalt were then bombarded with 5.0 Mev deuterons and the resultant proton groups were plotted. At each current setting of the spectrograph, the target was exposed to from 150 to 400 microcoulombs of deuterons, requiring from one to four hours per plate. The spectrograph field was changed in steps so as to cover an appreciable range of momentum, with the steps so arranged that the graphs from adjacent plates overlapped. With each set of plates at least one elastic was taken to calibrate the input energy. The ground and metastable states and some excited states were evident, but the yield was so low (a maximum of 36 counts per 1/2 mm for the ground state, for example,) that the statistics were poor, and weak peaks were entirely obscured. This was repeated for a portion of the spectrum with a bombarding energy of 5.8 Mev, but the results were no better.

Next the platinum-backed targets were bombarded at energies of 5.0 and 5.8 Mev. The input energy for each set of plates was again determined with at least one elastic group from a Formvar target and each exposure was of 600

microcoulombs duration. Because of the intense deuteron background from single and multiple scattering from the platinum backing, it was necessary to cover the plates with aluminum foil of sufficient thickness to stop the deuterons. The result of the plot of protons versus BR, covering the ground and first excited states, is shown in Figure 5. A typical plate at higher excitation showing the increase in density of levels, is shown in Figure 6. Figure 7 is a plot of the proton groups from the ground state to an excitation of 4.8 Mev with E_{in}, the deuteron bombarding energy, equal to 5.0 Mev.

In computing the momentum of a group of particles, the peak is replotted with abscissa expanded by a factor of 20.

A sample calculation, taken from plate 2IV follows:

Abscissa of index	11.040 cm
Minus abscissa of 1/3 height of peak	9.537
	Δ 1.503 cm
Measured beam to index distance	71.757 cm
	Δ 1.503
Diameter of proton trajectory	70.254 cm

$$\text{Radius of proton trajectory} = \frac{70.254}{2} = 35.127 \text{ cm.}$$

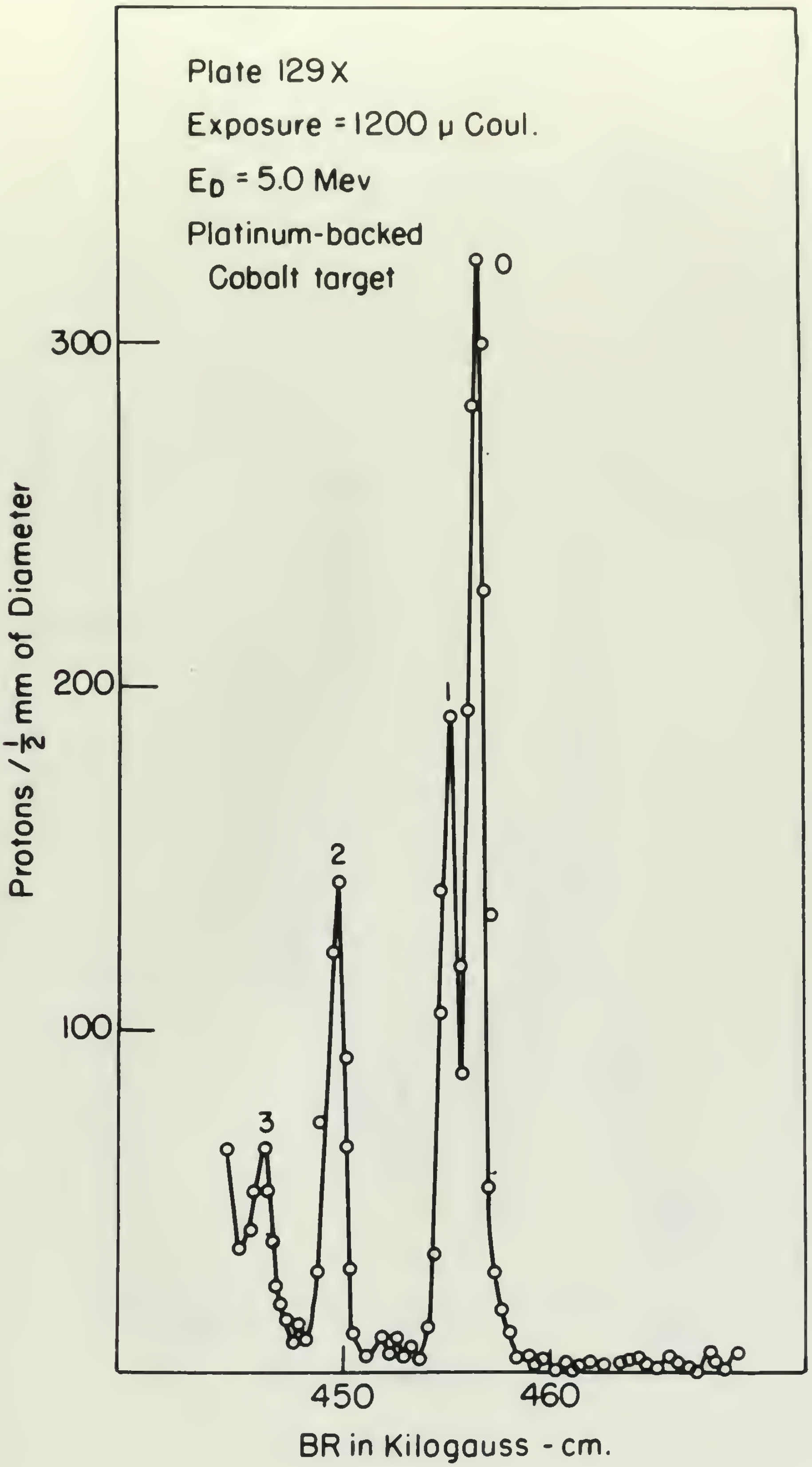


Plate 129X
Exposure = 1200 μ Coul.
E_D = 5.0 Mev
Platinum-backed
Cobalt target
0
1
2
3
300
200
100
Protons / ½ mm of Diameter
450
460
BR in Kilogauss - cm.

Figure 5

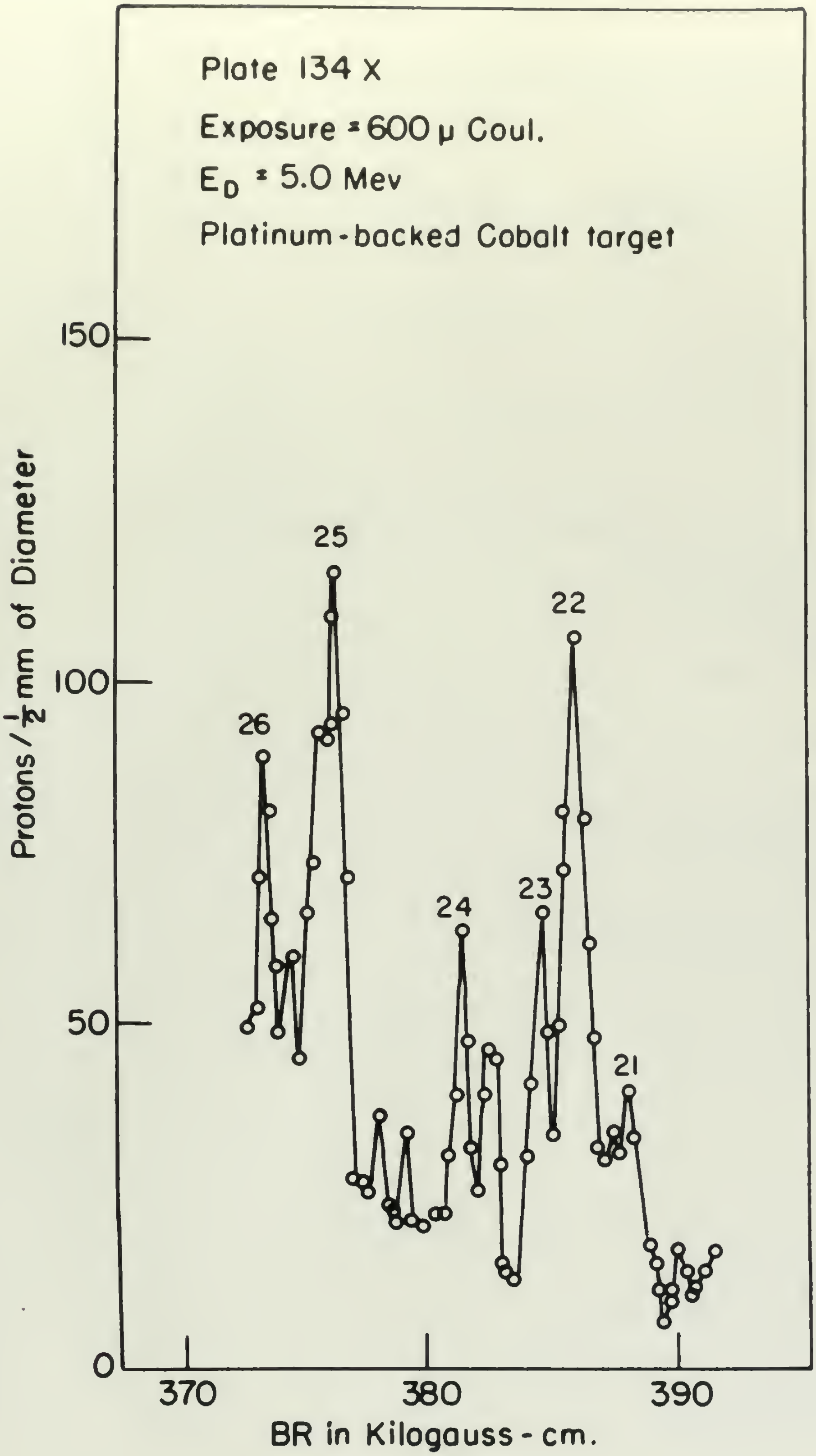
Plate 134 X
Exposure = 600 μ Coul.
E_D = 5.0 Mev
Platinum-backed Cobalt target
Protons / ½ mm of Diameter
150
100
50
0
26
25
24
23
22
21
370
380
390
BR in Kilogauss - cm.

Figure 6

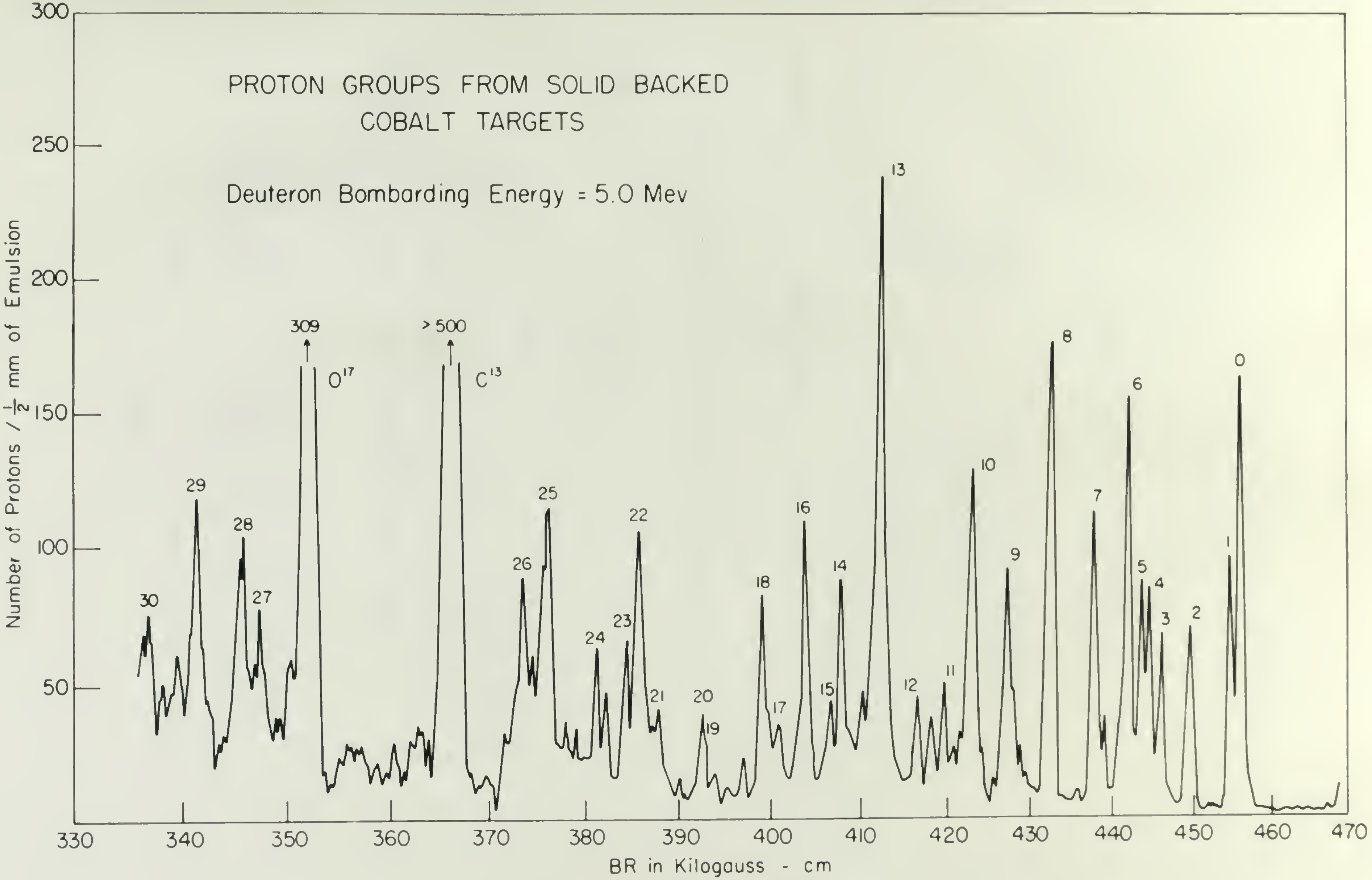

PROTON GROUPS FROM SOLID BACKED
COBALT TARGETS
Deuteron Bombarding Energy = 5.0 Mev
Number of Protons / $\frac{1}{2}$ mm of Emulsion
300
250
200
150
100
50
330
340
350
360
370
380
390
400
410
420
430
440
450
460
470
BR in Kilogauss - cm
309
O^{17}
> 500
C^{13}
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0

Figure 7

Frequency of spectrographic magnet fluxmeter = 21.300 mc.

$$B = \frac{21.300 \text{ mc}}{1.6545 \text{ mc/kg}} = 12.873 \text{ kilogauss}$$

$$BR = 12.873 \times 35.127 = 452.197 \text{ kilogauss-cm.}$$

From BR tables

$$E_o = 9.73470 \quad (BR = 452 \text{ kilogauss-cm})$$

$$\underline{845} \quad \text{(interpolation)}$$

$$9.74315 \quad \text{Mev}$$

$$E_{in} = 5.824$$

$$Q = \frac{(M_r - M_o)}{M_r} E_o - \frac{(M_r - M_i)}{M_r} E_i =$$

$$1.10168 \times 9.7432 - 0.96640 \times 5.8240 = 4.2785 \text{ Mev}$$

where $M_r = Co^{60} = 59.9364$ amu

$M_o = p = 1.00759$ amu

$M_i = d = 2.01419$ amu.

Relativistic correction = +1.1 kev. This relativistic correction came about by virtue of the fact that the Q-equation was derived for the nonrelativistic case.

The equation is

$$dQ = E_{in}^2 \frac{M_r^2 - M_i^2}{1842 M_r^3} + E_o^2 \frac{M_r^2 - M_o^2}{1842 M_r^3} - E_{in} E_o \frac{M_i M_o}{931 M_r^3}$$

$$Q + dQ = 4.2796 \text{ Mev.}$$

Finally, runs were made at 3.0 Mev to attempt to uncover the region obscured at 5.0 Mev by the intense carbon and oxygen peaks, and to repeat the measurement of the ground state Q-value. This was accomplished by holding the generator at 6 Mev and deflecting singly charged deuterium molecules. In a nuclear reaction the chemical binding energy of the molecule is negligible, each nucleus taking half the energy. The coulomb barrier, which is 6.6 Mev for compound nucleus formation, must have effectively reduced the (d,p) reaction probability at the energy, however, as only a negligible yield resulted.

In analyzing the results there are three ways to identify the residual nucleus of a reaction group. The first is to vary the composition of the target and note the corresponding variations in peak intensities. This was not intentionally done. The second is to match peaks with previously determined Q-value of known contaminants, and the third is by means of an energy shift. It is seen from the formula for E_o,

$E_o = \frac{M_r - M_i}{M_r + M_o} E_i + \frac{M_r}{M_r + M_o} Q$, where M_r is the mass of the residual nucleus, that the energy (and hence momentum) of a peak is a function of M_r. The output energy of a group

from Ca^{41}, for example, will shift 18 kev less per .8 Mev shift in input energy than that of a group from Co^{60}. Similarly a group from Br^{80} will shift 10 kev more per .8 Mev shift in E_{in}.

The known groups from carbon and oxygen were identified. A small peak between groups 10 and 11 at 5.0 Mev bombarding energy which was not reproduced at 5.8 Mev matches a known $Mg^{24}(d,p)$ group to within experimental error. Other known magnesium groups can be fitted, but not uniquely. The first excited level of Ni^{59}, seen in Kinsey's (n, γ) work, should lie just above the ground state of Co^{60} at a bombarding energy of 5.0 Mev, but was not seen. A structure on the low energy side of group 6 might be attributed to another group in Ni. All other groups of at least 50 counts per 1/2 mm of diameter yielded Q-values agreeing at the two input energies to within 12 kev when assigned to Co^{60}.

Above an excitation of 5 Mev, the proton background became large and widely variant between plates. This was thought to be due to a background of deuterons penetrating the foil by virtue of being deflected toward the normal to the foil. But it was shown that their range in the emulsion, even after passing through the foil at right angles,

was vanishingly small, and increasing the thickness of the foil only blocked out all protons. These plates were further confused by the appearance of proton tracks of all lengths up to the maximum expected. The reason for this high background may be closely-spaced, overlapping levels in Co^{60}, or it may be from the platinum backing. Lack of time prevented a controlled run on a bare platinum target. In the course of the experiment about 60 plates were exposed.

IV. RESULTS AND CONCLUSIONS

A. PROBABLE ERROR.

An estimate of the probable error in Q-values is gotten by examining the system of measurements and assigning probable systematic and random errors.

The random errors considered are:

(1) the spread in $B\rho$ resulting from finite slit widths,

(2) the spread in energy of emerging particles due to the variable thickness of cobalt the incident and reaction particles must penetrate,

(3) the finite width of the beam,

(4) the aberration of the 180° focusing magnet,

(5) the finite "reaction" angle subtended by the photographic plate, and

(6) small adjustments of the magnet currents necessary to keep the flux meter signal at the balanced position.

If one assumes an entrance slit width to the deflecting magnet of 1 mm, an exit slit width of 1 mm, and collimation of the entering and exit particles, one can make an order of magnitude estimate of the spread in $B\rho$ of the analyzed particles

as $dR/R = .5/600 = .008$. The energy loss in a thin, Formvar-backed target is estimated as 10 kev, yielding a fractional spread in BR of .0005. The width of the line on the target was measured as 0.7 mm, or $dR/R = .7/2 \times 350 = .001$. The focusing action of the 180° magnet gives a fractional second order spread of the order of $2(1 - \cos \theta) = 2\,\theta^2/2$. θ is estimated as $(2.5/2)/(35\,\pi/2)$, and $dR/R = .0005$. It has been estimated that[14] the plate subtends an angle of $90^\circ \pm 1/3^\circ$ from the beam line on the target.

$$dE = 2\sqrt{(M_1 M_0 E_1 E_0)}\ d \sin \theta/(M_0 + M_r), \text{ and}$$

$$dE/E = 2 \times 2\ (\tfrac{1}{3}\,\pi/180)/18 = .0013$$

for deuterons scattered from oxygen. This corresponds to $dR/R = .0006$. The two frequency settings each contribute errors of about 1:15,000, or $dR/R = .00007$. If we now take the square root of the sum of the squares of these estimated deviations and call this a gross approximation to σ, the standard deviation, we get $\sigma(BR)/BR = 1.6 \times 10^{-3}$ as shown in Table I.

If the deuteron elastic of plate 22Y is fitted to a normal distribution, $\sigma\ (BR)/BR = .065/70 = .9 \times 10^{-3}$. This agreement is as good as could be expected, considering the approximations made. A similar value for $\sigma\,(BR)$ is measured on well-developed cobalt (d,p) peaks.

RANDOM ERRORS

Source	Magnitude of Error $\sigma(BR)/BR$
Momentum spread of incident particles	.0008
Energy loss in cobalt	.0005
Width of line on target	.001
Aberration in 180° focusing magnet	.0005
Angle of observation	.0006
Deviations of B field	.0007
	$\sqrt{\sum \sigma_i / BR} = 1.6 \times 10^{-3}$

TABLE I

We do not actually have a Gaussian distribution, and it is the leading edge, not the mean, in which we are interested. If, nevertheless, we estimate the probable error as $.67\,\sigma/\sqrt{n}$, where $n \approx 250$ counts/peak, we get a random error of $.67 \times .9 \times 10^{-3}/16 = 1{:}25{,}000$. This is about the precision to which the position of the leading edge is recorded.

The systematic errors are more important and harder to estimate. These include:

(1) the calibration error of the polonium alpha groups,

(2) the departure of the average scattering angle from 90°,

(3) surface films on the platinum- and Formvar-backed targets,

(4) the uncertainty in the momentum of the polonium alphas,

(5) the error in recording index to emulsion track distance in a given microscope, due to a cant of the plate in the microscope,

(6) errors in the masses of the nuclei involved, and

(7) errors in the fundamental constants, e and c.

The beam to index distance, as determined from the positions of polonium alpha groups, is deduced from the average of several groups, each group having been averaged in several microscopes. Two such measurements were taken during the course of this experiment and the reproducibility, 1:27,000, may be taken as a measure of the error.

The departure of the scattering angle from 90° can, in principle, be measured by noting the energy of the elastics from two nuclides with a common bombarding energy, but surface films confuse the results unless widely different nuclides, such as gold and lithium, are used. A recent calibration of this type has not been made, but the general consistency of results in the laboratory leads to the belief that this angle is not greater than 20 minutes, which, as has been seen, leads to an error of about 6.5 kev in the calibration of 5 Mev deuterons from oxygen. In computing the Q of the ground state of Co^{60} this is balanced by a term

$$\frac{2}{60}\,(5{,}000 \times 10{,}000 \times 12)^{1/2} \sin\theta = 2 \text{ kev}$$

so that the probable error, taken as half the "limit of error", is 2 kev.

The surface film, which was due primarily to an accumulation of carbon on the face of the target, has been estimated in other experiments to be from 5 to 20 kev thick. This would presumably affect the long-bombarded platinum-backed targets

more than the short elastics from the Formvar targets. But in this case a positive correction would be applied to the E_0 of the ground state Co^{59}(d,p) reaction, increasing the measured Q, whereas our Q-value is already 20 kev greater than that of Bartholomew and Kinsey. A probable error of 5 kev is arbitrarily adopted.

The uncertainty in momentum of the polonium alphas is 1:5,000, or 1:2,500 in energy. Experience indicates that the probable error in reading a plate once on a microscope is .15 mm/700 mm = 1:5,000 in BR, or 1:2,500 in energy. Errors in nuclear masses and fundamental constants are negligible as compared with the above.

The total probable error in the determination of the ground state Q-value from one oxygen elastic and one (d,p) reaction is, then, the combination of the randomicity of the two measurements, the counting error of the two measurements, the surface film error, the polonium calibration error, the polonium momentum error, and reaction angle error. A tabulation of these errors is shown in Table II. The most important errors are those of film thickness and counting uncertainty.

TABULATION OF PROBABLE ERRORS IN DETERMINATION
OF Q-VALUE OF GROUND STATE

Source	Magnitude, dE (kev)
Random:	
Oxygen Elastic	± .04
Proton Group	± .16
Systematic:	
Counting error in elastic	± 2.0
Counting error in proton group	± 4.0
Surface film error	± 5.0
Polonium calibration error	± .38
Polonium alpha momentum error	± 2
Reaction angle error	± 2
	$\sqrt{\sum (dE)^2} = \pm$ 7.4 kev

TABLE II

For less well-developed peaks the probable error is increased. The excitation energy errors for groups which are seen on the same plate as the ground state, or on an adjacent, overlapping plate, is much less than the Q-value error, approaching 1 kev at low excitation.

B. RESULTS

Three long exposures were made to investigate the vicinity of the ground state of Co^{60}: one with a deuteron bombarding energy of 5.0 Mev against a Formvar-backed target, one with a bombarding energy of 5.0 Mev against a platinum-backed target, and the third with a bombarding energy of 5.8 Mev against the same solid-backed target. These three exposures resulted in Q-values for the ground state which were within eleven kev of agreement. The ground state Q-value determined in this work ($Q_o = 5.280 \pm 0.008$ Mev) corresponds to the arithmetic mean of the two extreme values, and the spread corresponds to a laboratory nonreproducibility of about ± 6 kev. The third value resulted from bombardment of the thinly coated Formvar target and was of lower yield and poorer definition than the two others. All three exposures, however, clearly showed the separation of the 60 kev metastable state; and the computed excitations of this level, as well as the other listed levels, were unmistakably reproduced on both major series of bombardments (those against the platinum-backed targets).

In each of the two major series of investigations (at $E_{in} = 5.0$ Mev and at $E_{in} = 5.8$ Mev), good agreement resulted for the relative positions of the lower states in comparison with the respective ground states. The first eleven states in each of the series agreed to within five kev of each other. These lower states were seen under conditions which remained unchanged within each series, but which were different for each of the two series. The exceptionally good agreement in excited states which resulted led to the use of the average of each of these excited states in determining the Q-values of these levels. These Q-values, then, are the difference of the average ground state Q-value, which was determined less accurately, and the precise excitation energies. For the higher excited states, there being no simple correspondence in excitation energies, the Q-values of each level were determined by averaging the Q-values determined at each bombarding energy. Also, at these higher excitations, the increased number of weak levels arising from both contaminants and Co^{60} itself made resolution of the major peaks difficult. All levels attributed to Co^{60}, however, were in agreement to within 12 kev. In some instances it was possible to resolve a complex peak such that, by subtracting a minor peak, agreement was attained with the corresponding peak as determined at a different bombarding energy. This

technique was used only when it seemed justified by an obviously smaller structure indicated on a major peak.

Table III is a summary of the Q-values, excitation energies, appropriate probable errors, and approximate relative yields of those attributed to energy levels in Co^{60}.

C. COMPARISON WITH PREVIOUS RESULTS

The ground-state Q-value determined here, $Q_o = 5.280 \pm 0.008$ Mev, is in fair agreement with the values 5.20 determined by Bateson and Pollard[6], 5.44 ± .2 determined by Harvey[1], and 5.31 determined by Hoesterey[7]. The more precise work of Bartholomew and Kinsey[3], when the binding energy of the deuteron (2.226 Mev) is subtracted from their highest energy gamma-ray, results in a Q of 5.260 ± 0.006, a difference of 20 kev.

Table IV compares the excitation energies from this work with those found by Bartholomew and Kinsey and by Bateson and Pollard. It is seen that the excitation energies, particularly of the lower states are in excellent agreement. It is also of note that those low lying states of Bartholomew and Kinsey which stem from transitions indicated by strong homogeneous gamma-rays agree exceptionally well.

D. CONCLUSIONS

The metastable state in Co^{60} 59 kev above the ground state is nicely brought out by the present work, and it is

EXPERIMENTAL RESULTS

Peak	Q (Mev)	E* (Mev)	Relative Intensity
0	5.280 ± .008		1.0
1	5.220 ± .008	.060 ± .003	.6
2	4.994 ± .008	.286 ± .003	.5
3	4.835 ± .008	.445 ± .003	.4
4	4.767 ± .008	.513 ± .003	.5
5	4.723 ± .009	.557 ± .005	.5
6	4.659 ± .009	.621 ± .004	.9
7	4.488 ± .008	.792 ± .003	.7
8	4.268 ± .008	1.012 ± .003	1.0
9	4.043 ± .009	1.237 ± .005	.6
10	3.886 ± .009	1.394 ± .004	.8
11	3.747 ± .010	1.533 ± .006	.3
12	3.617 ± .010	1.663	.3
13	3.455 ± .010	1.825	1.5
14	3.278 ± .010	2.002	.5
15	3.219 ± .010	2.061	.7

TABLE III

EXPERIMENTAL RESULTS

Peak	Q (Mev)	E* (Mev)	Relative Intensity
16	3.126 ± .010	2.154	.5
17	2.988 ± .010	2.292	.2
18	2.910 ± .015	2.370	.5
19	2.665 ± .010	2.615	.1
20	2.650 ± .010	2.630	.2
21	2.489 ± .012	2.791	.3
22	2.409 ± .015	2.871	.6
23	2.356 ± .012	2.924	.4
24	2.242 ± .012	3.038	.4
25	2.069 ± .012	3.211	.7
26	1.971 ± .012	3.309	.4
27	1.054 ± .012	4.226	.4
28	.974 ± .013	4.306	.6
29	.855 ± .012	4.425	.7
30	.709 ± .015	4.571	.5

TABLE III (Continued)

COMPARISON OF EXCITED STATES OF Co^{60} (Kev)

Peak	Present Work	Bartholomew and Kinsey	Bateson and Pollard
1	60 ± 3		
2	286 ± 3	285*	390
3	445 ± 3	445*	
4	513 ± 3	512*	
5	557 ± 5		
6	621 ± 4	619*	
7	792 ± 3	796*	810
8	1012 ± 3	1012*	
9	1237 ± 5	1236	1280
10	1394 ± 4	1376	
11	1533 ± 6	1520	
12	1663		
		1760	1730
13	1825	1840	
14	2002		
15	2061		
16	2154	2135	2170
17	2292	2307	
18	2370		
19	2615	2583	
20	2630		

TABLE IV

Peak	Present Work	Bartholomew and Kinsey	Bateson and Pollard
21	2791		
22	2871		
23	2924	2900	
24	3038		
		3120	
25	3211		
26	3309	3300	
		3460	
		3800	
		4130	
27	4226		
28	4306		
29	4425		
30	4571		

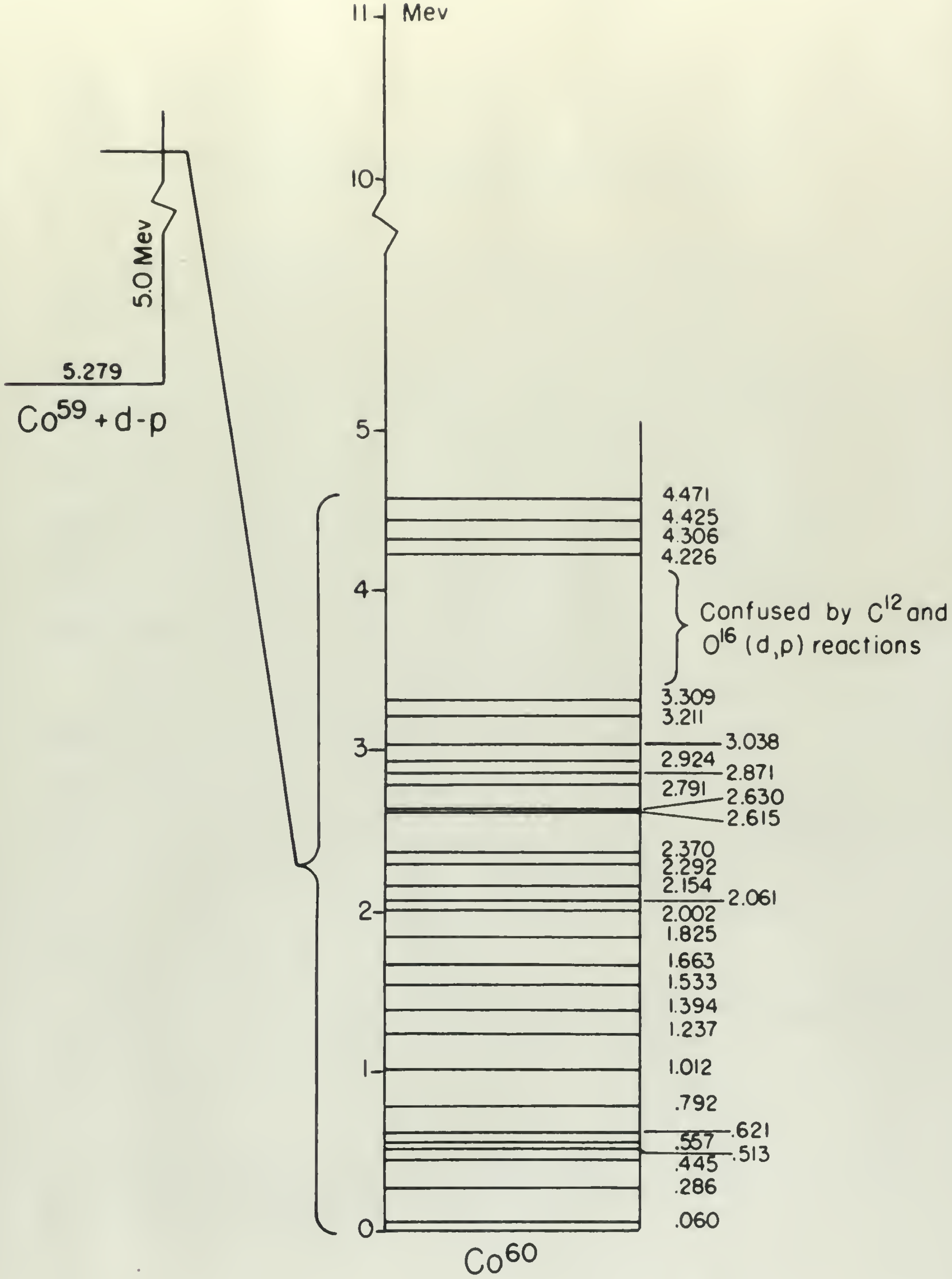
*Levels whose existence is inferred from strong homogeneous gamma rays.

TABLE IV
(Continued)

clear that Bartholomew and Kinsey were measuring gamma-rays to the ground state of Co^{60}, not to the metastable state. They state[3] that, should this be the case, the intensity of gamma-rays to the metastable state is less than 10 percent of those to the ground state.

As an explanation for this, it is noted that there is a resonance in the Co^{59} neutron capture cross section at 123 ev, which state presumably influences the capture of thermal neutrons if we make the reasonable assumption[15] that the energy level spacing here is of the order of tens of kilovolts. It is reasonable further to assume, then, that s-wave neutrons are captured into the (f) 7/2 ground state of Co^{59} to form a 4- state, and that electric dipole radiation to the 5+ ground state of Co^{60} exceeds the magnetic quadrupole radiation to the 2+ metastable state by a factor greater than 10.

The level density as presented in Figure 8 is, unfortunately, not conclusive, as it is felt that in the region of excitation above 1 Mev there are some Co^{60} levels whose intensities are not sufficiently high uniquely to identify them as such. Above an excitation of 4.8 Mev, no useful information was obtained on level densities. A lower limit on level densities below this figure is set, however, and it is easily seen by comparison with Bartholomew and Kinsey's gamma spectra of iron and nickel that this odd-odd nucleus has a more complex spectrum than that of its even-odd neighbors.



ENERGY LEVELS IN Co^{60}

Figure 8

APPENDIX A

Proposal for the Determination of the Spin of Co^{60}

The accepted values[1] of the spins and parities of the ground and first excited states of Co^{60} are 5+ and 2+, respectively. The shape of a newly discovered beta from the ground state of Co^{60} to the first excited state of Ni^{60} leads Keister and Schmidt[2] to assign values of 4+ and 1+, respectively, to the above levels, although such assignments cannot be reconciled with the lack of a beta decay from the first excited state of Co^{60} to the ground state of Ni^{60}.

In order to attempt to resolve this question it is proposed that the new magnetic spectrometer be used to measure the angular distribution from 0° to 120° of protons from the $Co^{59}(d,p)Co^{60(.059)}$ reaction, utilizing Butler's[3] theory of angular distibution as a function of the angular momentum of the captured neutron.

The shell model and Schmidt diagram concur in assigning odd parity to the ground state of Co^{59} $(I = 7/2)$, so one

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1. Goldhaber and Hill, RMP, 24, 179, (1952)
2. Keister and Schmidt, PR, 93, 140, (1954)
3. Butler, PRS, A208, 559, (1951)

would expect the orbital angular momentum of the neutron, l_n, captured in going to the first excited state of Co^{60} to be 1 or 3. If l_n were found to be 1 it would rule out the assignment of 1- to the first excited state of Co^{60}, whereas if $l_n = 3$, both 1- and 2- are allowed states of this level.

Using deuterons of 6.4 Mev energy in c.m.s. (6.4 x 61/59 = 6.6 Mev in laboratory system) and an outgoing c.m.s. energy of 6.4 - 5.23 = 11.63 Mev, it is clear from the figures in Butler's article that the differential cross-section for the reaction would peak at about 22° for $l_n = 1$, 30° for $l_n = 2$, and 51° for $l_n = 3$, all angles in c.m.s.

In order to convert laboratory system angles to c.m.s. one must add to the measured angles, ϑ, the quantity $(\Theta - \vartheta)$, where

$$\sin(\Theta - \vartheta) = \frac{\sin\vartheta \times \text{vel of c. of m.}}{\text{vel of proton in c. of m.}}$$

$$= \frac{\sin\vartheta \sqrt{\frac{2E_d}{m_d}} \quad 2/61}{\sqrt{\frac{2}{m_d} \quad (11.63 \text{ Mev}) \; 60/61}}$$

$$= \sin\vartheta \sqrt{\frac{6.6}{2 \times 11.63} \quad \frac{61}{60} \quad \frac{2}{61}}$$

$$= .0176 \sin\vartheta \quad \left[(\Theta - \vartheta) = 1.0^\circ \quad \text{at } \vartheta = 90^\circ\right]$$

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